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MEASUREMENT OF MISSILE POSITION AND ATTITUDE BY LASERS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents a method for measuring the position and attitude of spinning rockets and missiles by the use of multiple laser trackers. While the immediate application of this system is in range instrumentation, it has potential as a guidance system — particularly for a guidance system using midcourse or terminal correction.

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ABSTRACT (Continued)

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ABSTRACT (Concluded)

The main advantage of a laser tracker system over existing camera tracker systems is that it would permit near real time reduction of range test data. Based on estimates made by contractors furnishing laser equipment, it appears that the system will exceed the accuracy of existing camera tracking systems and that hardware exists in a high state of development for this application. Implementation into hardware and testing will be required to determine the total system accuracy and to isolate engineering problems which may be associated with its development.

The program objective is to obtain rocket position and attitude for determination of vehicle aeroballistic parameters from flight tests. The constraints are as follows:

1) Process real time or near real time data.
2) Obtain accuracy equal to or better than currently available.
3) Obtain data regardless of flight abnormalities.
4) Obtain high reliability for data acquisition.
5) Extend testing capability to low ambient light situation including night operation.
6) Reduce overall cost of data acquisition and reduction.

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1. Introduction

A ground-based laser system for determination of vehicle position, attitude, and roll rate on missile and rocket test ranges has been proposed.[1,2,3] The system includes three ground-based transmitter/detector tracking stations each incorporating one pulsed and one CW laser of different frequencies. On-board the vehicle, two different types of retroreflecting arrays are required. A series of conventional corner cubes form a band around the perimeter of the vehicle body at one axial location and, in conjunction with a pulsed laser, form a conventional laser radar tracking system. The three CW lasers and a series of roof type prisms which are aligned with the roll axis and mounted on the vehicle's surface form the attitude sensing system. In this report, the array of roof type prisms is referred to as single plane corner reflectors. The location of the on-board reflectors is shown in Figure 1. Further details on the geometry of the arrays will be presented in the next paragraph.

As a vehicle flies downrange, it is tracked with the laser radars which provide continuous illumination of the vehicle with the CW lasers. Assuming a rolling vehicle, a pulse will be returned to the three tracking stations at the CW laser frequency each time the vehicle makes a revolution. The phase relationship between these three CW pulses and the missile position obtained from the tracking stations provide the data needed to determine the vehicle attitude.

2. System Concept

a. Single Plane Corner Reflector

The beam incident angles θ and β on a single plane corner reflector (roof prism) are shown in Figure 2. The single plane corner reflector has the property of returning an incident, columnated beam to the transmitter site for a range of incident angles θ and a unique angle β of 90°. In Figure 3 an attempt is made to illustrate the dependence

[1]Pell, Kynric M. and Conard, Robert G., Preliminary Study of Roll Rate Determination Utilizing a Corner Reflector, July 1971, Report No. RD-TM-71-8.

[2]Aeroballistics Directorate, Free Flight Technology Program, Chapter 8, FY74 Activity Report, Report No. RD-75-3.

[3]Pell, Kynric M.; Russell, Mark J.; Nydahl, John E.; Lindberg, William R.; A Laser System for Determination of Rocket Attitude and Roll Rate, US Army Research Office, Durham, North Carolina, Final Report, Report No. UWME-DR-4061051, Grant No. DHHC04-74-G-0063.

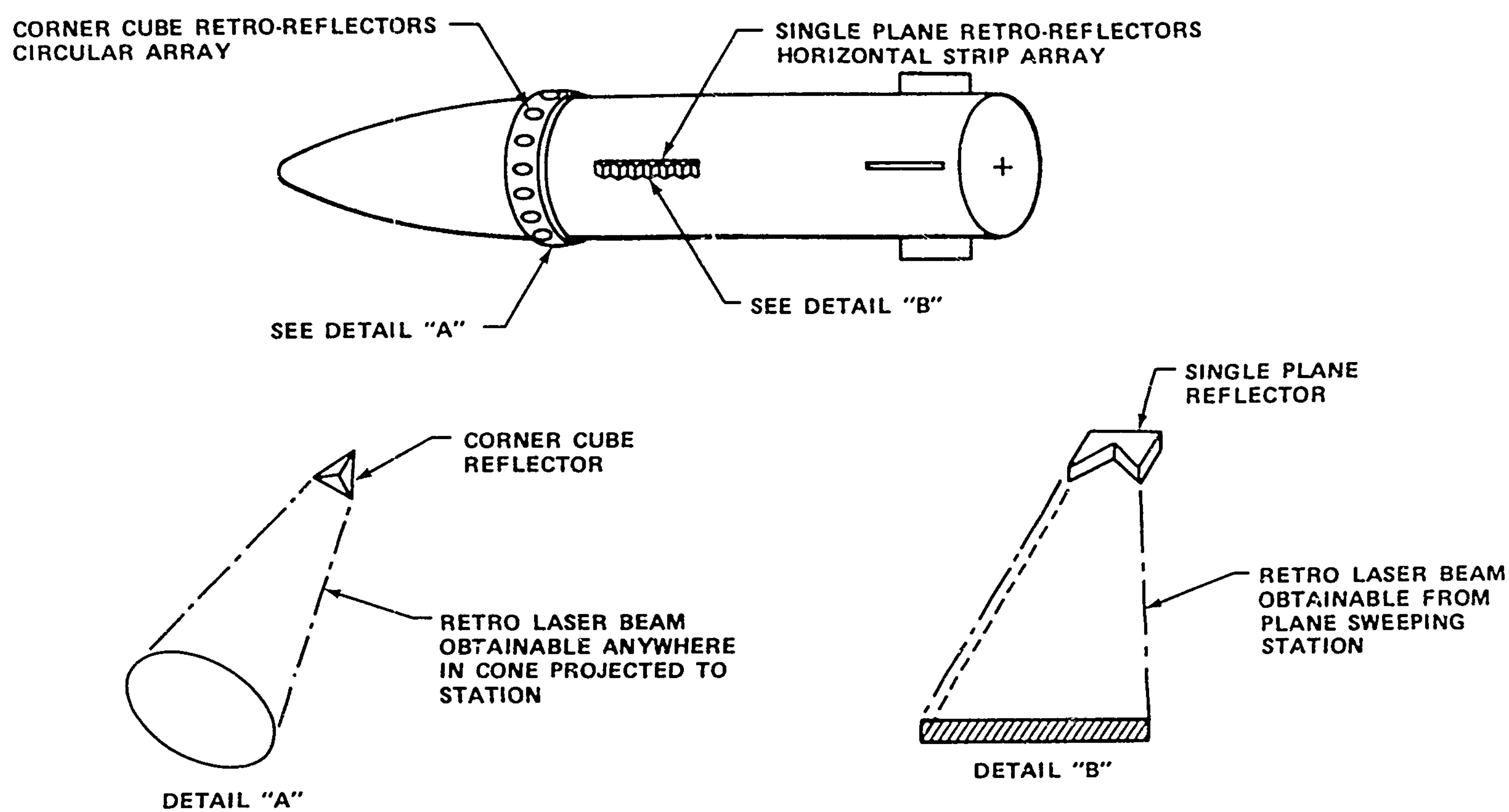


Figure 1. Target reflector schematics.

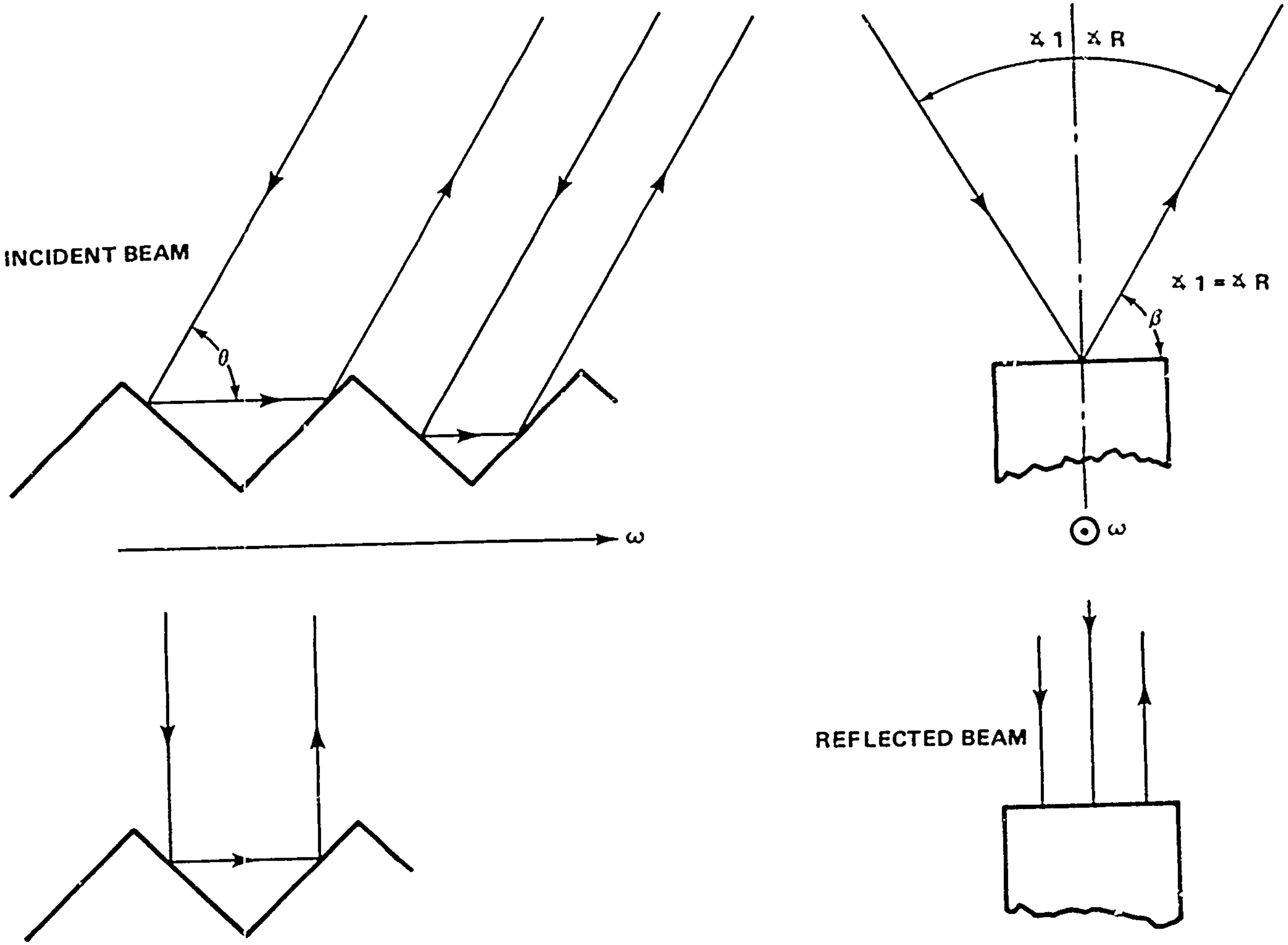


Figure 2. Properties of a single plane corner reflector.

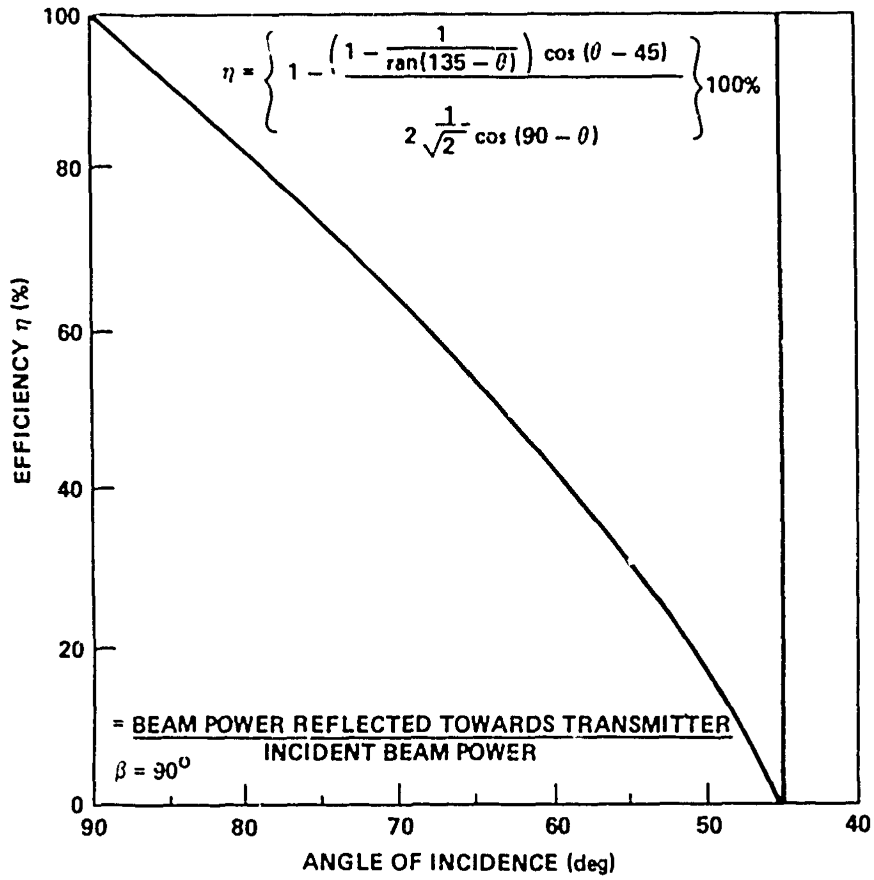


Figure 3. Efficiency of a single plane corner reflector.

of the reflector efficiency on the incident angle θ. It may be seen that for $90^\circ < \theta < 45^\circ$ and $\beta = 90^\circ$, at least a portion of the incident beam is returned to the transmitter site.

b. Use of a Single Plane Corner Reflector on a Rocket

The system concept involves the mounting of at least one single plane corner reflector on a spinning rocket. The corner reflector will be aligned with the geometric longitudinal axis of the missile such that the angle θ is measured in a plane containing the roll axis and the angle β is in a plane normal to the roll axis. If the rocket is illuminated with a laser beam, the reflected beam will return to the transmitter in the unique situation when $\beta = 90^\circ$ or when the plane defined by the normal to the corner reflector and the roll axis contains the coordinates of the transmitter/detector station. Assuming that the rocket

remains fixed in space and rolls at an angular rate cycles second, a pulsed type signal would be received at each fixed transmitter detector site every 1/. seconds.

c. The Use of a Two-Station System to Determine Pitch Rate

Consider now a system composed of two transmitter/detector stations again illuminating a rolling rocket equipped with a single plane corner reflector and again fixed in space. Figure 4 illustrates this situtation.

At time t_1 the roll attitude of the rocket is such that a return pulse is received at station 1 (Figure 4). After a period of Δt, the rocket roll attitude has changed by an amount t at which time a return pulse is received at station 2. For a fixed ω and station geometry, it may be seen that the time between reception of return pulses at stations 1 and 2 is directly related to the pitch angle δ_1 for small yaw angles δ_2. If $\delta_1 = 0$, the signals will be synchronous, and as δ_1 increases so will Δt.

d. Generalization of the System

The two-station system can be expanded to a three-station system which can provide data to determine pitch and yaw simultaneously. Analysis of the data from the ground based detectors for pitch and yaw attitude requires that the position of the flight vehicle be known. It has been proposed that vehicle position be obtained using laser radar trackers which would be colocated with a CW laser system used for attitude determination. It is anticipated that the laser radar system will require equipping the flight vehicle with standard corner cube retroreflectors in addition to the single plane corner reflector array.

3. Mathematical Descr ption of a System

To determine vehicle attitude, three ground laser transmitter/detector stations are required. The discussion and analyses to follow will assume a vehicle fixed in space and rotating at constant ω.

A CW laser beam is reflected back to the tracking station from an angle plane corner reflector that is mounted parallel to the vehicle's axis of symmetry when this station is contained in the plane formed by the vehicle roll axis and a normal vector to the plane corner reflector. For a vehicle fixed in space and rotating at a constant angular frequency ω, the detector y_ω pulse signals per unit of time. For an actual flight where the missile is moving and the roll rate is not constant, modification to the analysis will be required.

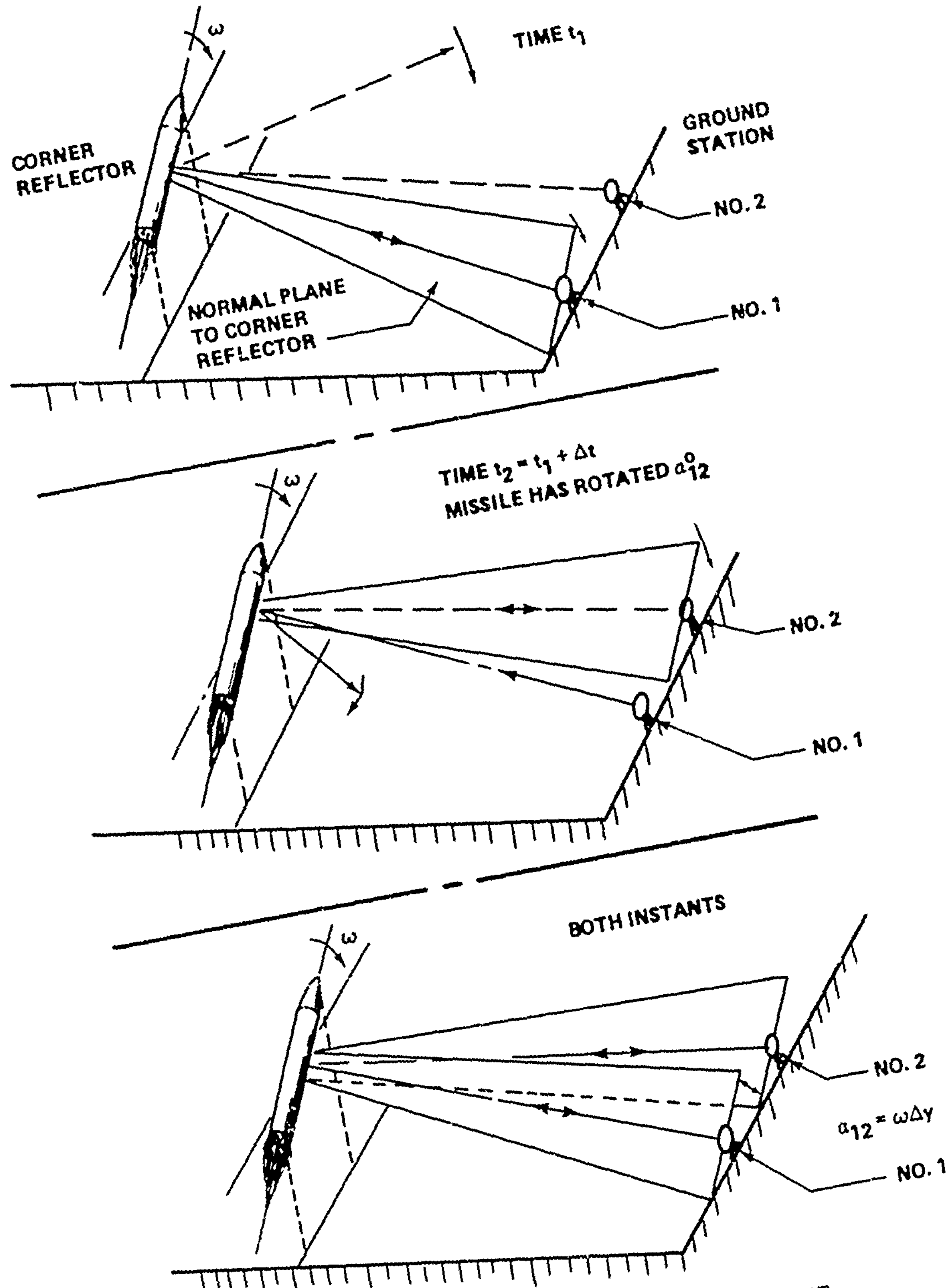


Figure 4. Two-station tracking system.

The mathematical description may be facilitated by defining three coordinate systems. An earth-fixed Cartesian system (Figure 5) is defined in the following way:

a) The origin is located at the launch site.

b) Y positive is in the downrange direction.

c) X is crossrange.

d) Z is positive in the vertical upward direction.

e) (X, Y, Z) forms a right hand system.

A vehicle based coordinate system (Figure 5) is defined such that:

a) The origin is located at the vehicle center of gravity.

b) ω coincides with the vehicle roll axis with the positive direction toward the nose.

c) η is perpendicular to ω and parallel to the x-y plane of the earth fixed system.

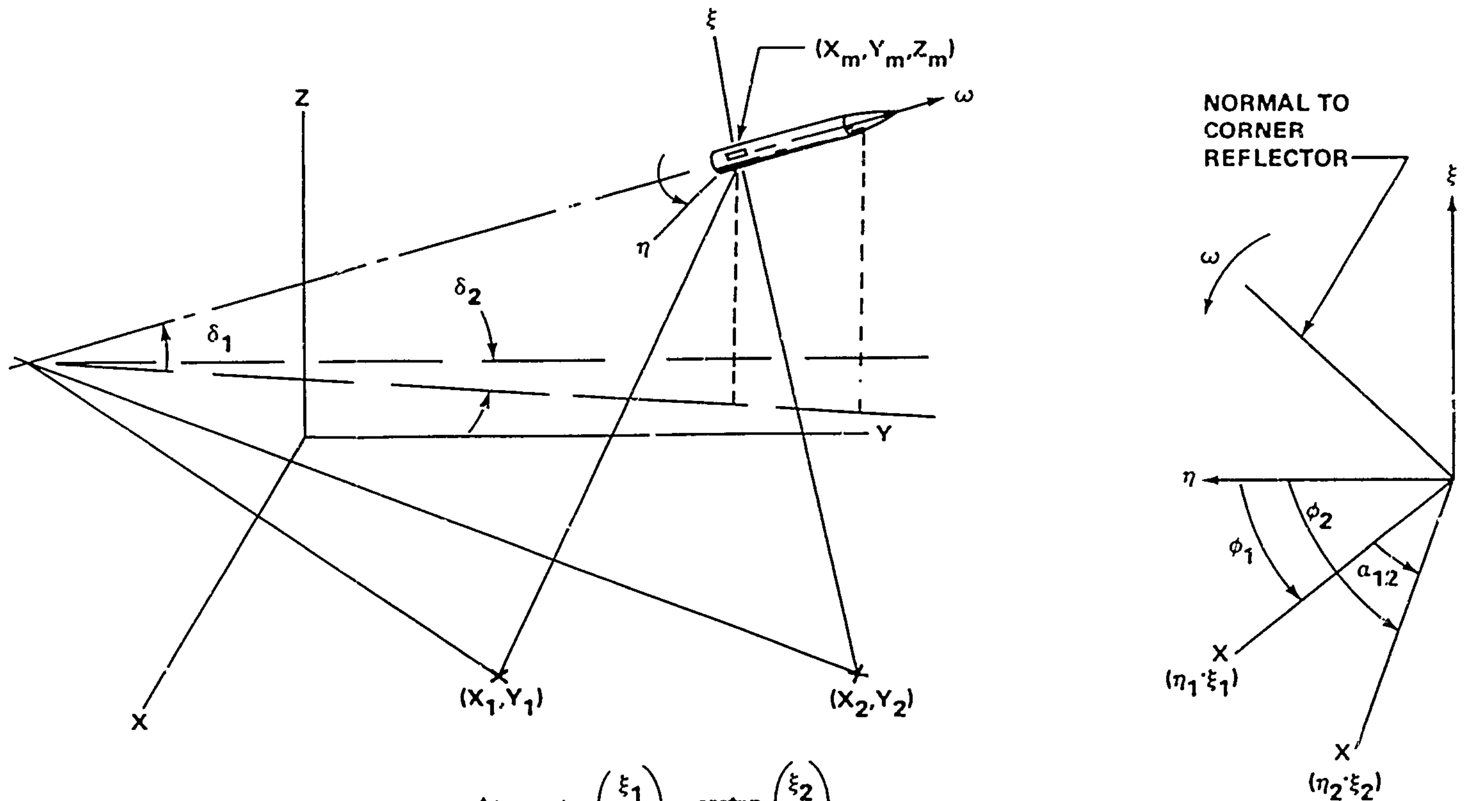
d) ξ is perpendicular to η and ω and positive in a direction that made (η, ω, ξ) a right hand system.

The intermediate system (x^1, y^1, z^1) has the same orientation as the earth fixed system, however the origin is located at the vehicle's center of gravity.

One approach to analysis of the system involves a description of the location of the ground transmitter/detector station location in terms of the vehicle based η, ω, ξ coordinates. Let $\bar{R}_i$ be the position vector of the ith ground tracking station in the earth fixed system with x component x_i, y component y_i, and z component z_i. Furthermore, let $\bar{R}_m$ be the position vector of the vehicle's in the earth fixed system with components x_m, y_m, z_m. The term $\bar{x}_i^1$ position vector represents the center of gravity of the ith ground tracking station in the (x^1, y^1, z^1) system. In this case, $\bar{x}_i^1 = \bar{x}_i - \bar{x}_m$ (or $x_i^1 = x_i - x_m$, $y_i^1 = y_i - y_m$, and $z_i^1 = z_i - z_m$).

The position vector of the ith ground tracking station in the (η, ω, ξ) coordinate is $\bar{\eta}_i$. Now $\bar{\eta}_i = \bar{A}\,\bar{x}_i^1$.

The matrix A is obtained by considering a rotation δ_2(yaw) about the z^1 axis, where the transformation matrix is given by



$$a_{12} = \omega \Delta t = \arctan\left(\frac{\xi_1}{\eta_1}\right) - \arctan\left(\frac{\xi_2}{\eta_2}\right)$$

Figure 5. Geometric analysis.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \delta_2 & \sin \delta_2 \\ 0 & -\sin \delta_2 & \cos \delta_2 \end{bmatrix}$$

followed by a rotation δ_1(pitch) about the x^1 axis, where the transformation matrix is given by

$$\begin{bmatrix} \cos \delta_1 & 0 & -\sin \delta_1 \\ 0 & 1 & 0 \\ \sin \delta_1 & 0 & \cos \delta_1 \end{bmatrix} .$$

The product of these two matrices taken in the appropriate order yields

$$\begin{bmatrix} \cos \delta_1 & \sin \delta_1 \sin \delta_2 & -\sin \delta_1 \cos \delta_2 \\ 0 & \cos \delta_2 & \sin \delta_2 \\ \sin \delta_1 & -\sin \delta_2 \cos \delta_1 & \cos \delta_2 \cos \delta_1 \end{bmatrix}$$

so that

$$\begin{bmatrix} \xi_i \\ \eta_i \\ \omega_i \end{bmatrix} = \begin{bmatrix} \cos \delta_1 & \sin \delta_1 \sin \delta_2 & -\sin \delta_1 \cos \delta_2 & z_i^1 \\ 0 & \cos \delta_2 & \sin \delta_2 & x_i^1 \\ \sin \delta_1 & -\sin \delta_2 \cos \delta_1 & \cos \delta_2 \cos \delta_1 & y_i^1 \end{bmatrix}.$$

Therefore,

$$\xi_i = (z_i - z_m) \cos (\delta_1) - \sin(\delta_1)\cos(\delta_2)(y_i - y_m) + \sin(\delta_1)\sin(\delta_2)(x_i - x_m)$$

$$\eta_i = (x_i - x_m) \cos(\delta_2) + \sin(\delta_2)(y_i - y_m)$$

$$\xi_i = (z_i - z_m)\ \sin(\delta_1)\ - \sin(\delta_2)\cos(\delta_1)(x_i - x_m) + \cos(\delta_2)\cos(\delta_1)(y - y_m)\ .$$

These forms for the equations are based on the assumption that pitch is positive for upward rotation of the nose, and yaw is positive for the nose pointing to the left of the range center line. Often the opposite convention is adopted for yaw, particularly in the reporting of flight test data. For this convention, the transformations have the following form:

$$\eta_i = (x_i - x_m)\ \cos(\delta_2)\ - \sin(\delta_2)(y_i - y_m)$$

$$\omega_i = (x_i - x_m)\ \sin(\delta_2)\ \cos(\delta_1) + \cos(\delta_2)\ \cos(\delta_1)(y_i - y_m) + \sin(\delta_1)(z_i - z_m)$$

$$\xi_i = (x_i - x_m)\ - \sin(\delta_2)\ \sin(\delta_1)\ - \cos(\delta_2)\ \sin(\delta_1)(y_i - y_m) + \cos(\delta_1)(z_i - z_m)\ .$$

These equations were chosen because they conform to the standard direction chosen for flight test data.

Considering the (η, ω, ξ) coordinate system shown in Figure 5, it may be seen that for a constant roll rate ω the relationship between the time for signal reception at stations 1 and 2 in terms of their location is

$$\alpha_{12} = \omega\Delta t_{12} = \theta_2 - \theta_1\ .$$

A three ground station system provides three pulses (one for each station per rotation of the vehicle) which may be viewed as two independent time intervals; that is,

$$\Delta t_{12} = \frac{1}{\omega}\left\{\arctan\left(\frac{\xi_2}{\eta_2}\right) - \arctan\left(\frac{\xi_1}{\eta_1}\right)\right\}$$

and

$$\Delta t_{13} = \frac{1}{\omega}\left\{\arctan\left(\frac{\xi_3}{\eta_3}\right) - \arctan\left(\frac{\xi_1}{\eta_1}\right)\right\}\ .$$

Assuming that the ground station positions are known in the (x, y, z) coordinate system, and that the vehicle position is determined using the

laser tracking system, these two equations can be expressed in terms of only two unknowns; that is, pitch (δ_1) and yaw (δ_2):

$$\Delta t_{12} = \frac{1}{\omega}\left\{\arctan\left[\frac{-\sin(\delta_2)\sin(\delta_1)(x_2-x_m) - \cos(\delta_2)\sin(\delta_1)(y_2-y_m) + \cos(\delta_1)(z_2-z_m)}{\cos(\delta_2)(x_2-x_m) - \sin(\delta_2)(y_2-y_m)}\right]\right.$$

$$\left. - \arctan\left[\frac{-\sin(\delta_2)\sin(\delta_1)(x_1-x_m) - \cos(\delta_2)\sin(\delta_1)(y_1-y_m) + \cos(\delta_1)(z_1-z_m)}{\cos(\delta_2)(x_1-x_m) - \sin(\delta_2)(y_1-y_m)}\right]\right\}$$

$$\Delta t_{13} = \frac{1}{\omega}\left\{\arctan\left[\frac{-\sin(\delta_2)\sin(\delta_1)(x_3-x_m) - \cos(\delta_2)\sin(\delta_1)(y_3-y_m) + \cos(\delta_1)(z_3-z_m)}{\cos(\delta_2)(x_3-x_m) - \sin(\delta_2)(y_3-y_m)}\right]\right.$$

$$\left. - \arctan\left[\frac{-\sin(\delta_2)\sin(\delta_1)(x_1-x_m) - \cos(\delta_2)\sin(\delta_1)(y_1-y_m) + \cos(\delta_1)(z_1-z_m)}{\cos(\delta_2)(x_1-x_m) - \sin(\delta_2)(y_1-y_m)}\right]\right\}$$

These equations can be solved iteratively on the computer by first assuming the yaw to be zero and solving for pitch using the most pitch sensitive equation. Using these values (δ_1 = solution, δ_2 = 0) as an initial guess, a Newton-Raphson solution of the simultaneous equations is effected.

4. Range Placement of Laser Trackers

To determine all six degrees of freedom of a missile trajectory, three laser tracker sites would be required. The most accurate measurements of missile attitude are obtained when the tracker is at 90° to the missile axis. Therefore, it would be advantageous to locate the sites as far away from the missile flight path as possible. But the power requirements due to safety and other considerations places a limit on the distances at which the sites can be located away from the rocket flight path. For the US Army Missile Command (MICOM), Redstone Arsenal, Alabama, test range, the following locations appear to be feasible: (a) station 1 would be located approximately 3000 feet from the launcher on a line perpendicular to the flight path; (b) station 2 would be located 2000 feet downrange and 3000 feet from the flight path; and (c) station 3 could be located on the opposite side of the flight path in certain selected positions. Station 3 could also be located farther downrange from stations 1 and 2 but at different distances from the flight path. In all locations, the angle between a line to the rocket and the rocket axis must be such that a reflected signal can be received by the laser site (Figure 6).

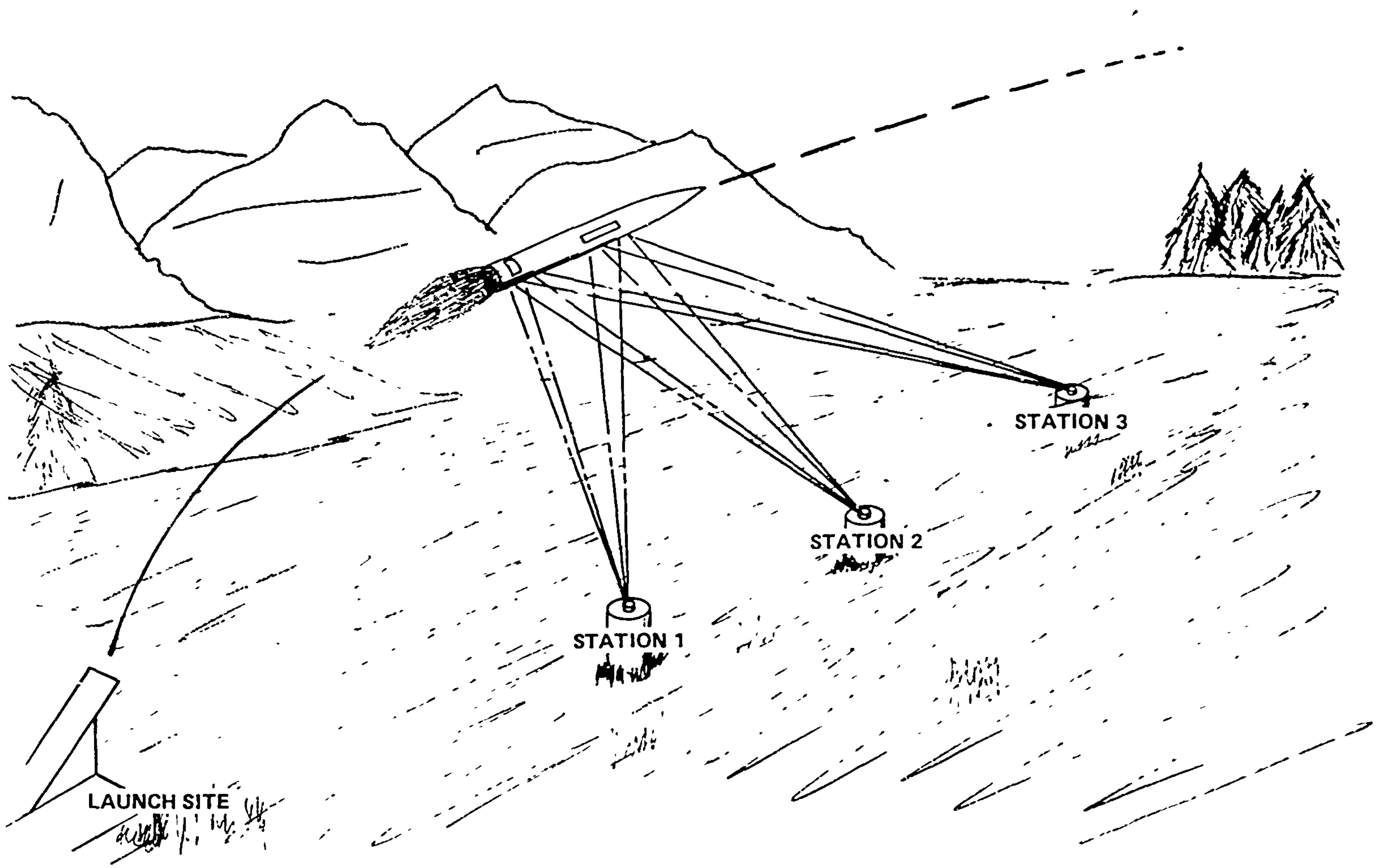


Figure 6. Three-station tracking system.

The objective of this arrangement would be to measure the boost phase of the trajectory of a small rocket. If the objective was to measure a different segment of the trajectory, other arrangements would be required.

5. On-Board Equipment

The equipment located on-board the missile consists of two reflector strips, one being a circumferential ring around the base of the rocket and the other being a longitudinal strip on the exterior surface of the rocket and parallel to the rocket axis. These reflecting surfaces are totally passive. Thus, there are no active elements located on-board the rocket when the use is for range instrumentation. The thickness of the reflectors can be made arbitrarily thin by increasing the number of individual prisms (Figure 7). However, some thicknesses of the reflector may result in optical interference. The thickness chosen must be such that signals are not lost at the look angles during which the missile is tracked.

If the system is used in a guidance mode, the addition of a command link and an actuator would be required. The guidance computer would be ground based.

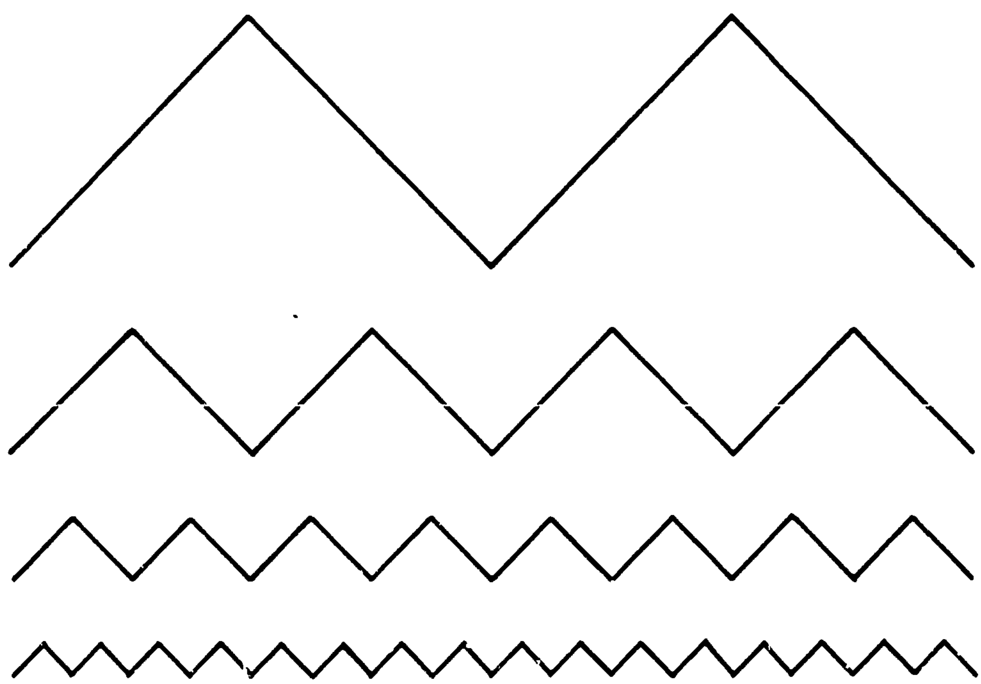


Figure 7. Reflectors made arbitrarily thin by increasing the number of prisms.

6. Laser Trackers

The laser tracker must perform two functions during the flight of the rocket. First, it must track and record the rocket positions as a function of time. Second, the laser tracker system must record the return signals from the roof reflectors as the rocket rotates. It is from the latter that the rocket attitude is determined.

The most probable mechanization of this scheme would use two lasers of different frequencies, whereby one would track the missile and a second would record the return pulses from the roof reflectors. The tracking laser could and almost certainly would be a pulsed laser while the attitude measurement would be a CW laser. In the selection of the frequencies, there would be consideration of safety and background scatter.

As an operational characteristic of the system, means must be provided for acquiring the rocket at the initial segment of the trajectory over which the rocket is to be tracked. If the initial position is the launcher, a television camera or some bore sighting equipment could be used. However, if the initial segment of the trajectory is some position downrange, some acquisition mechanism will be required. This need not be complicated since the trajectory of the rocket will be known for the nominal case and may entail only a time position pointing of the laser tracker.

7. Conclusions

The use of multiple lasers for range instrumentation appears to be straight forward. All subsystems to be utilized in this application are in a high stage of development and laser trackers are presently utilized on some test ranges.

As in all optical systems, limitations may occur as a result of fog, dust, rain, etc. While this does not impose any serious restrictions on its use as range instrumentation, it may, however, limit its use for other applications such as a guidance system.

This system in its present concept does not readily lend itself to tracking from the rear. With the proposed implementation, the best locations for the transceivers are from the sides or looking at right angles to the rocket in flight. Since the target is the rocket being tested, some freedom should exist, at least during research and development, in the choice of location of the retroreflectors.